# Final Report
# MURI Western Consortium
# High Energy Microwave Sources

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**NORTHROP GRUMMAN**

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## DIRECTOR'S OVERVIEW

This report covers the final seven-month period August 1, 1999 through March 14, 2000 and contains a detailed description of the work conducted by the Western MURI Consortium on High Energy Microwave Sources. The participating institutions are the University of California, Davis (Lead Institution), Stanford University, Northrop Grumman Corporation, UCLA, and UC Berkeley.

As described in more detail in the body of the Report, this has been an extremely productive program. Of particular note, there have been several major transitions and spin-offs. First, the UC Davis researchers involved in the development of a compact, high brightness, picosecond, kiloampere, MeV electron source for coherent millimeter wave generation have conceived of a novel use in the medical screening and treatment area. Specifically, by combining this electron source with a synchronized, TW level, high repetition rate fsec laser, they are developing a "table-top," tunable X-ray Compton light source. As discussed in detail, the applications range from high resolution mammography and angiography to X-ray phototherapy. This high potential payoff novel concept has recently been selected for three year funding by the National Cancer Institute during a competition for innovative, noninvasive cancer detection and treatment strategies. The team includes MURI researchers from UCD and Stanford as well as laser scientists from LLNL and Industry together with surgeons and radiologists from UCD and UCLA. Another exciting transition concerns the novel microfabricated "klystrino" device conceived by Stanford MURI researchers for application either singly or in large arrays for affordable, lightweight millimeter wave systems. They have received significant Air Force funding (from the Philips Laboratory) to develop this as a practical source. This also offers the possibility of realizing miniature high gradient accelerators with broad applicability ranging from next generation lithography to the abovementioned medical diagnostic and treatment concept. A preliminary design study has indicated that this would make it possible to realize a Compton X-ray diagnostic and treatment device on a platform essentially the size of a standard Varian Clinac machine. A further transition involves Stanford MURI researchers who have received support from the Los Alamos National Laboratory to design and fabricate a GW-class annular beam klystron employing state-of-the-art manufacturing and conditioning techniques required for maintenance of the necessary rf gradients for the microsecond pulse durations. It is anticipated that this will result in the first demonstration of a kilojoule, microsecond duration, GHz source thereby possibly eventually resulting in the funding of the considerably more compact permanent magnet focussed multiple beam klystron conceived by the Stanford MURI team and which is believed to be technically ready for immediate industrial production and system insertion. It should also be noted that the Stanford MURI work on multiple beam devices has sparked interest in the Navy for the development of devices for shipborne application.

In addition to the above transitions, the participating Western MURI institutions have been selected to deliver 2 invited talks at major scientific meetings , published 1 paper and had an additional two accepted and 10 submitted to refereed scholarly journals, contributed seven chapters to an HPM book, and presented 13 talks at conferences.

The overall goals of this DoD program are described in detail in the original FY94 MURI Topic Description and are aimed at addressing critical, fundamental research issues in support of DoD high energy microwave source needs for communication, radar, electronic warfare, and high energy microwave weapons. The Western Consortium possesses the broad ranging capabilities required to address these issues: slow and fast wave device design capability, UHV surface science analysis and plasma deposition capability, high vacuum electron beam device fabrication facilities, extensive microwave and millimeter wave test facilities, device and circuit modelling capability, and DoD systems and applications expertise. In the following, I have again reiterated the specific goals of this MURI activity and have highlighted the major achievements and accomplishments during the past year August 1, 1999 through March 14, 2000.

As mentioned above, we have focussed on the directives of the MURI program, which has been titled since its inception in 1994 as "High Energy Microwave Sources", and whose focus was subsequently sharpened to emphasize support for stated research goals at the Air Force Research Laboratory (AFRL) in addition to the more general DoD high energy microwave source requirements for communications, radar, electronic warfare, and directed energy weapons. Two specific goals have been consistently highlighted by AFRL scientists at MURI Review and Organizational Meetings as well as at scientific conferences:

1. The generation of multi-Gigawatt microwave pulses, with duration of one microsecond or more, at frequencies near 1000 MHz.
2. The generation of very high peak and average power at W-Band (approximately 100 GHz).

Based on thermal scaling, it is generally accepted in the field that the power capability of microwave tubes is roughly proportional to the square of the wavelength. This means that a 1-GW device at 1 GHz is essentially equivalent to a device producing 100 kW at 94 GHz. Hence, the two AFRL goals are closely related.

The actual realization of a device to serve each objective listed above may involve different principles or design approaches; but, in both cases, there are two common, quite fundamental limitations, which must be overcome:

1. The electron emitter (cathode) must be capable of providing the necessary current in the electron beam, consistent with the electron optics required to produce the correct beam size.
2. The output structure (also known as the "extraction" circuit) must be capable of converting the kinetic energy in the electron beam into electromagnetic energy, without developing unacceptably high surface rf gradients, which can lead to breakdown (pulse shortening).

In addition, there are two other fundamental, enabling technologies required to provide the foundation for the development of the above mentioned high microwave energy sources:

1. Electron guns of the required voltage, perveance, and beam quality.
2. Low loss, rf output windows.

The Western MURI program is strongly directed at the investigation of these fundamentals, with extensive, basic research being performed on cathodes, windows, and rf breakdown at UCD/Stanford and with electron gun research and development conducted at Northrop Grumman and separately with electron gun modelling at UCLA. In addition, the realization of the desired devices is being explored, using a number of different concepts and configurations which address the basic limitations cited above, in addition to the research performed on the limiting mechanisms. Principal among these design approaches are the following:

For the 94 GHz requirement, harmonic gyrotrons and peniotrons, as well as broadband gyro-TWT amplifiers are being investigated (the latter of which possesses important radar usages). First, a collaboration between UC Davis, Northrop-Grumman, the Naval Surface Warfare Center (Crane), and the Air Force Research Laboratory (Phillips Lab) has been initiated to investigate fourth and eight harmonic gyro-devices employing the newly developed Northrop cusp electron gun goal (funded under MURI). The ultimate aim of these fundamental studies is to make possible the development of compact, lightweight, low voltage, permanent magnet based 25-100 kW average power sources. The second collaboration involves UC Davis, NTHU, and UCLA in basic theoretical and experimental studies of 35 and 94 GHz multi-megawatt, broadband gyro-TWTs for high power radar.

As mentioned above, an extremely promising and completely novel approach to high power generation at W-band has been proposed. It involves modules of several micro-machined, PPM-focussed "klystrinos", whose outputs may be paralleled through waveguides or with a quasi-optical combiner and "smart tube" controls. This method can produce megawatts at 94 GHz, and has a form factor which makes it extremely attractive for radar and directed energy applications. This device concept represents a dramatic advance (in both price and performance) from conventional linear-beam, millimeter wave RF sources which are limited to power levels of roughly 5 kW peak and 500 W average power due to the limited current that can be transported through the submillimeter beam tunnels required in these devices and which precision machining of the parts and individual assembly. The Stanford 94 GHz klystrinos are predicted to produce 100 kW peak output power and 1 kW average power using a 110 kV, 2.7 A beam and will be manufactured using LIGA microfabrication technology. The klystrons can be combined in a module using a $TE_{10}$ rectangular to $TE_{01}$ circular mode converter. A module can have either 500 kW output power at a narrow bandwidth or the individual klystron frequencies can be spaced to produce 1% bandwidth at 100 kW, at lower gain. In a parallel effort, a sheet beam klystron is also being developed at W-band with a predicted output power of 1 MW per device. Currently, LIGA fabricated circuits from both SRRC and Sandia National Laboratory are under test.

Two high power, Cusp electron guns have been delivered by Northrop Grumman. This innovative electron gun has been developed under both MURI and DURIP funding to address key DoD needs. In a collaboration between UCD, Northrop Grumman, Naval Surface Warfare Center (Crane) and the AFRL (Phillips Lab), the guns will be employed in a number of high power, harmonic gyro/penio, millimeter wave devices to satisfy the Ka-band and W-band requirements of the AFRL and other DoD organizations. The Cusp electron gun was designed to produce 70 kV, 3.5 A, axis-encircling electron beams with low velocity spread and has been successfully tested at the reduced voltage of 10 kV.

Three experiments employing the Cusp guns are underway. Mr. Ron Stutzman's sixth-harmonic slotted gyrotron will reduce by a factor of six the magnetic field needed by a W-band gyro-device and is predicted to generate 50 kW at 94 GHz with a device efficiency of 20%. The AutoCAD drawings for his circuit have been sent to several machine shops for bid. Mr. Larry Dressman (Crane) will attempt to further improve the efficiency of the novel peniotron interaction. Researchers in Japan have recently achieved 70% electron efficiency in a third-harmonic peniotron. However, since the cavity was only critically coupled, the device efficiency was a more modest 35%. By strongly overcoupling the cavity, our second-harmonic peniotron is predicted to yield a device efficiency exceeding 50% and generate 125 kW at 30 GHz. Mr. Steve Harriet (Crane) will further advance our concept that harmonic gyrotron amplifiers can produce higher power because of their improved stability. His device will double the efficiency of our previous second-harmonic gyro-TWT amplifier, which yielded a record-breaking gyro-TWT output power of 200 kW. The axis-encircling electrons from the Cusp gun will not be constrained by the mode-selective circuit's maxima and minima that compromised the interaction efficiency of the previous experiment with a MIG electron beam. The second-harmonic Cusp-gun $TE_{21}$ gyro-TWT amplifier is predicted to generate 50 kW at 30 GHz with 20% efficiency, 30 dB gain and a bandwidth of 4%.

In addition, a very high performance, first-harmonic, 94 GHz gyro-TWT amplifier will be tested. By operating in the low loss $TE_{01}$ mode, the amplifier is capable of continuous operation. The MIG electron gun is being fabricated at NTHU. The amplifier is predicted to produce 100 kW at 94 GHz with an efficiency of 20% efficiency, 30 dB gain and 5% bandwidth. The technology from this device has been transferred to the company, Micramics, for their development of a higher power, second-harmonic, $TE_{02}$ gyro-TWT amplifier.

Stanford and UC Davis are working on the fabrication of a 100 kW peak power, 1 kW average power, RF source at W-band. The LIGA process used to fabricate the klystron circuit body enables multiple devices to be duplicated on the same substrate. This can be used to produce multiple klystron modules in a very compact package. As an example, a four klystron module would produce 400 kW peak and 4 kW average power at 94 GHz in a 4" x 4" x 14" package. The use of a relatively high cathode voltage (110 kV) for a 100 kW source results in increased circuit length. Given the small circuit dimensions, increased length is critical to achieving high average power at 94 GHz. The LIGA fabrication also significantly improves the intrinsic Q of the output circuit, greatly reducing the RF circuit losses.

The use of PPM focusing in high voltage klystrons was successfully demonstrated with the 75 MW, 11.4 GHz, NLC klystrons. This is important for modular klystron design, since the low-leakage-field PPM focusing allows the individual klystrons to be mounted close to each other without affecting beam transmission.

Modeling devices with rectangular geometry usually requires time consuming, coarse resolution, 3-D, computer codes. A protocol has been developed to build an equivalent 2-D model of the klystron and both reduce run time and increase the accuracy of the model.

UCD and Stanford have been collaborating in studies of alternate cathode science and technology with the aim of developing a reproducible, robust, high current density oxide cathode. Oxide cathodes have always had attractively low work functions, but they have been plagued by their variability in performance. A plasma deposition/implantation process for coating barium and strontium oxides on nickel substrates has been developed. Several barium-strontium cathodes have been fabricated with current densities up to 30 $A/cm^2$. Further improvements in current density have been limited by the excess water vapor present in the large vacuum chamber. The vacuum system has recently been upgraded with a 4000 liter/sec cryopump replacing a 100 liter/sec turbopump. Plasma deposition/implantation of the oxide layer directly on the cathode surface will eliminate the major sources of cathode poisoning. Oxide cathodes produced with this technique may have significantly improved emission properties and certainly will have consistent performance due to the control of the deposition/implantation process. Recently, a pulsed Nd laser system has been acquired under DURIP funding to replace the pulsed vacuum arc plasma deposition technique with laser ablation.

A collaboration with Sandia National Laboratory has been formed to study the use of scandium in connection with plasma-deposited oxide cathodes. Sandia is investigating a similar technique for producing oxide cathodes for use in thermoelectric power cells.

A spin-off of the plasma deposition oxide cathode program has led to new advances in metalization of ceramics for both high voltage standoff and RF window applications. This method is applicable to the standard alumina ceramic and also to high purity technical ceramics that have proven very difficult to metalize and braze. An initial experiment has been conducted using several hot-isostatic-pressed, 99.9% pure, alumina strips. This material is very difficult to metalize and braze using standard moly-manganese metalization. The alumina strips were metalized using a plasma deposition process. The strips were brazed to copper pull-tabs and then subjected to a series of pull tests. The adhesion of the plasma deposited metalization to the ceramic was very good. All the pull test samples removed some of the base ceramic material before the joint failed. A cross-consortium-collaboration between Stanford and CPI has been awarded a Phase I, Manufacturing Technology contract to study the baseline properties of conventional ceramic to metal braze joints and to develop the plasma deposition metalization process. Funding is provided by ONR and program management is handled by the American Competitiveness Institute.

Stanford and UC Davis have conducted a series of experiments to investigate the critical mechanisms involved in pulsed rf breakdown. This research has examined fundamental issues such as microparticle contamination, grain boundaries, residual gas, pulse duration, field emission, and surface plasma.

In the microparticle contamination study, it was found that small particles (0.5-5  m) did not contribute significantly to rf breakdown. At relatively low power levels, breakdown sites were observed to follow grain boundaries. This was presumed due to trapped gas in the grain boundaries that is liberated during rf processing.

Breakdown experiments have recently focused on investigating the behavior of rf breakdown and dark current at pulse lengths ranging from 80 ns to 1500 ns, and in various vacuum conditions. Experiments with nitrogen and $CO_2$ have shown that dark current seems to be gas species dependent. There was negligible change in dark current and no reduction in the breakdown field when nitrogen was introduced into the system from $10^{-11}$ to $10^{-6}$ Torr. When $CO_2$ was slowly introduced into the system ($10^{-10}$-$10^{-5}$ Torr), the dark current increased by a factor of two; however, the cavity could be processed to the same breakdown field. This indicates that dark current may not be directly related to breakdown.

Breakdown fields depend on pulse length (at narrow pulse lengths), and closely approach CW breakdown fields ($dE/d\tau \approx 0$) for sufficiently long pulses. For pulse lengths between 800-1500 ns, the breakdown fields followed a $\tau^{-1/2}$ dependence. At shorter pulse durations (<800 ns), a transition in the breakdown field from $\tau^{-1/2}$ to $\tau^{-1/3}$ occurs. The physical mechanism that lowers the breakdown field time behavior from $\tau^{-1/2}$ to $\tau^{-1/3}$ at shorter pulse lengths is currently being investigated.

During previous years, a number of device concepts were developed under MURI by the Stanford and UC Davis researchers to address the need for compact, multi-GW, microsecond duration sources operating at L-Band (1-2 GHz). These include the Gigawatt Multiple Beam Klystron (GMBK) and the coaxial ubitron which is a combination of a coaxial backward wave oscillator (BWO) and a coaxial free electron maser (FEM) also featuring periodic permanent magnets to focus the hollow electron beam resulting in a very lightweight, efficient package. Further research has ceased on these device concepts, since sufficient funds have not been available under MURI to support proof-of-principle experimental tests. However, efforts continued aimed at working with industry to secure funding to demonstrate the concept. This has included working with Small Business who have the capability to fabricate and test the demonstration device. In addition, as mentioned above, Stanford researchers are working under separate LANL funding to produce a GW-class annular beam klystron.

The success of the beam and RF simulations of the GMBK led to discussions of spin-off applications of the multiple beam klystron (MBK) technology. A generic MBK that can easily be scaled to the AWACS specifications was designed in a previous period. The reduced voltage and increased bandwidth of MBK's are a good fit for this application. The device can easily produce the required power, bandwidth and efficiency with a beam voltage of 40 kV. The tube requires an electromagnet, unlike the GMBK. It uses 19 beamlets in a hexagonal pattern. The beams are positioned in the central reentrant region of "H" shaped TM01 cavities. During the past year, there has been considerable interest expressed by the DoD in MBKs as can be seen from the Proposed Advanced Development Initiative in Vacuum Electronics prepared by the DoD Executive Agent and the Tr-Service Vacuum Electronics Steering Committee. In another potentially significant transition, Stanford researchers have initiated discussions with the medical treatment industry regarding the replacement of conventional klystrons with reduced voltage MBKs.

Work continued on the development of photoenhanced gated silicon field emitter arrays. Previously, the leakage current to the gate had posed significant problems for the operation of our field emitter arrays. After extensive investigation, it appears that the surface crystal structures of surfaces around the emitters had been damaged during the reactive ion etch. The process has since been modified and preliminary tests have shown significant improvement. We measured up to 0.4 mA of stable field emission current and obtained up to 7 orders of magnitude linearity on the Fowler-Nordheim plot from a 1mm-by-1mm (50-by-50) sample and also performed CW photo-excited measurements at various gate voltages. Arrays fabricated in the latest run have been bonded and are undergoing test. As mentioned previously, Bechtel has provide funding because of the potential application for high speed displays.

At UCLA, research continued on the development of a modified (stretched) particle-in-cell (PIC) code which separates the global electromagnetic modes from the localized electrostatic modes which provides considerable increase in speed for those problems for which the approach is applicable. This was employed to simulate a helix BWO as well as a multi-signal amplifier. They also performed the modelling of the single anode magnetron injection gun beam to be used in the proposed UCD TE01 94 GHz gyro-TWT. They have also employed their code to simulate the performance of mode selective extended interaction circuits including one to be employed by the University of Maryland for the output cavity of a new version of their phigtron device.

The UCB component of the MURI-West effort focused on a number of key areas:

1. Parallel extension of the XOOPIC code. The electromagnetic version is now functional, and has been tested on a number of parallel computers.
2. 3d extension of the XOOPIC code. The design and algorithms for the third dimension have been completed. Boundary conditions and testing are not yet complete. The initial test problem is the MURI-West klystrino.
3. Multipactor simulations. In collaboration with Univ. Michigan, they have continued the study of multipactor physics. In particular, several publications have resulted from the study of single surface multipactors fed by electromagnetic radiation, of importance in window breakdown, for example. High energy impact capable of generating x-rays has been demonstrated, as well as space charge effects and a previously unknown cutoff impact energy.
4. In collaboration with Stanford and UC Davis students and researchers, they have begun studies of the enhancement of field emission at a metal surface due to a plasma sheath formed at the surface in an attempt to understand the physics of high gradient rf breakdown.

The major emphasis of the UCB MURI funded research activities is to develop a three-dimensional version of their XOOPIC simulation code to address the 3-D nature of the devices relevant to high energy microwave source requirements. This has necessitated the need to create a parallel version of the code. Other work has included a collaborative study of breakdown on dielectric surfaces together with the University of Michigan, Texas Tech, and the University of Maryland.

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May 2000

# Simulation Efforts On Compact High Power Gyrotron Amplier

This is the Final Report on work performed under the support of the MURI program (High Energy Microwave Sources). The objectives of this work were to carry out research on the generation of high energy microwave radiation from relativistic electron beams and to explore means of improving performance. This report describes the status of gyrotron extended interaction oscillators and the resulting bandwidth of a inverted gyrotwystron using the proposed oscillator as its output cavity.

## I. INTRODUCTION

The early motivation for the work on gyrotrons has been the search for microwave power sources to heat plasma to fusion temperature. Lately, these devices have found other applications for the Department of Defense in systems such as high-resolution, millimeter-wave radar or highly directional communication. These applications all demand wide bandwidth and high power . To satisfy both requirements, one approach is to use gyro-TWT amplifiers. The other approach is to make use of modified gyro-klystron amplifiers.

Due to the relatively high Q of the resonant uncoupled cavities, bandwidth in a klystron tends to be fairly narrow. To alleviate this deficiency, the concept of extended interaction klystron[1,2] was introduced four decades ago. The new concept uses long resonant cavities, each with several interaction gaps. Approximated synchronism between the beam velocity and the forward-wave component of the standing wave in the resonator is required, and the resulting bandwidth capability is somewhere between a conventional kylstron and a TWT. In a gyrotron, the coupling between adjacent cavities is provided by a taper section which produces imperfect mode conversion between adjacent resonant modes. By increasing the number of coupled cavities, the overall Q can be reduced because the cavity field is peaked at the location closer to the output and as a consequence, a major portion of wave power can easily come out.

The bandwidth capability of a modified gyro-klystron depends on the bandwidth overlapping among the input, bunching, and output sections. This report will address only the issues of input and output sections. Using a clustered cavity[3] for the bunching section to enhance the overall bandwidth will not be discussed. In the followings, the numerical algorithm to simulate the mode conversion in a wave guide with non-uniform cross-section is briefly descried in Section II. Section III presents simulation results concerning the effect on Q from using different number of cavities. Section IV addresses the issue of bandwidth capability of an inverted gyrotwystron using the extended interaction cavity as its output section.

## II. NUMERICAL ALGORITHM

In simulating the performance of an extended interaction cavity, the mode conversion in the taper region plays the essential role in providing the coupling between the adjacent cavity modes. In 1984, Capland at UCLA has described in his Ph.D. dissertation[4] the algorithm of mode conversion for waveguide with non-uniform cross-section. Since this is the first time we activated this portion of the algorithm, it will be briefly described below. For each $TE_{mn}$ mode supported by a waveguide, its governing equations can be reduced from three spatial dimensional Maxwell's equations to an equivalent set of one spatial dimensional, time dependent, inhomogeneous transmission line equations[4-6].

$$\frac{\partial E_{Tmn}}{\partial t} = -c\frac{\partial B_{Tmn}}{\partial z} + \omega_{cmn} B_{Lmn} - c B_{Tmn}\frac{r_w'(z)}{r_w(z)}\left(\frac{m^2}{k_{mn}^2 - m^2}\right) + c\frac{r_w'(z)}{r_w(z)}\sum_{l\neq n} K_{mnl}B_{Tml}$$

$$-\frac{2L_p}{N_p U_{mn}}\left(\frac{\omega_B}{\omega_{c0}}\right)^2\frac{r_w(0)}{r_w(z)}\bullet\sum_j V_{\perp j}\delta(x_j,y_j)$$

$$\frac{\partial B_{Tmn}}{\partial t} = -c\frac{\partial E_{Tmn}}{\partial z} + cE_{Tmn}\frac{r_w'(z)}{r_w(z)}\left(\frac{m^2}{k_{mn}^2 - m^2}\right) + c\frac{r_w'(z)}{r_w(z)}\sum_{l\neq n} K_{mnl}E_{Tml}\frac{(1 - m^2/k_{ml}^2)}{(1 - m^2/k_{mn}^2)}$$

$$\frac{\partial B_{Lmn}}{\partial t} = -\,\omega_{cmn}E_{Tmn}\ . \qquad (2)$$

Here $\omega_{cmn} = ck_{mn}/r_w(z)$ is the waveguide cutoff frequency,

$$\left(\frac{\omega_B}{\omega_{c0}}\right)^2 = \frac{5.875 \times 10^{-5} I_b}{K_{\perp 0}^2 b_{z0}},\ K_{\perp 0}^2 = \frac{r_w(0)\omega_{c0}}{c},\ \ U_{mn} = J_m^2(k_{mn})\,(1 - m^2/k_{mn}^2)$$

$$K_{mnl} = \frac{2\,k_{mn}\,k_{ml}\,J_m(k_{ml})}{(k_{ml}^2 - k_{mn}^2)\,J_m(k_{mn})}$$

and the electron beam is modeled by a collection of $N_p$ macroelectrons distributed over length $L_p$. Each macroelectron represents $N \bullet L_p/N_p$ electrons where N is the number of electrons per unit length. Here, c is the speed of light, $\omega_{co}$ is $ck_{mn}/r_w(0)$, $\vec{V}_j$ is the electron velocity, and $\beta_{z0}$ is the average beam axial velocity divided by c.

Following the approach of Solymar[7], the waveguide radius in our scheme is allowed to be an arbitrary continuous function of axial position, allowing one to model profile interaction circuits and mode conversion. As was shown in the attached manuscript, the simulation result from the above algorithm agrees very well with the theoretical prediction[8] in mode conversion in the taper region.

## III. EXTENDED INTERACTION CAVITY

**Table I**
Design Parameters For a 35 GHz Extended Interaction Gyrotron Oscillator

| | |
|---|---|
| Beam Voltage | 70 kV |
| Beam Current | 40 A |
| Modes | $TE_{02}$, $TE_{03}$, $TE_{04}$ |
| $\alpha = v_\perp / v_\parallel$ | 1.5 |
| Harmonic(s) | 2 |
| Interaction Length (L) | 9.5 cm |
| Cutoff Frequency $f_c = \omega_c / 2\pi$ | 33.8GHz |
| Waveguide Radius $R_1$ | 0.991 cm |
| $R_2$ | 1.437 cm |
| $R_3$ | 1.882 cm |
| Output Taper Angle($\theta$) | 20° |
| Guide Field ($B_0$) | 6.617 kG |
| Guiding Center Location | 0.436 cm |

In the eighties, the research activities in complex cavity were very active. At that time, only two cavities coupled through either a step or taper were considered. Here, we will first present our simulation results for two coupled cavities ($TE_{03}$ / $TE_{04}$) using the same total axial length as that of the three coupled cavities to be presented later. Our intention is to address the issue of increasing the number of coupled cavities to reduce the Q of the output cavity. The dimensions of the cavity are $L_1$ = 3cm($TE_{03}$), $L_2$ = 4.5cm($TE_{04}$) and $L_{12}$ = 2cm and the parameters in Table I were used in simulations. The time evolution of the $TE_{03}$ and $TE_{04}$ modes is shown in Fig. 1a. Both modes grow together at the same growth rate and saturate at the same time with the output waves dominated by the desired $TE_{04}$ mode. The nonlinear efficiency has reached about 35%. The steady-state axial field profile is displayed in Fig. 4b. Because of the usage of two coupled cavities, the peak of the electric field is shifted toward the output plane from the result if a single cavity is used. As a result, the cavity Q becomes only about 560 even though cavity length of 9.5 cm and output taper angle of 20 degrees were used. If a single $TE_{03}$ cavity is used, the Q becomes more than 1000. The desired output mode is a high order $TE_{04}$ mode and so the radial inhomogeneity in the strength of electron-wave coupling may play a role in affecting device performance. Fig. 2a shows the radial dependence of electron-wave coupling strength and the initial electron beamlet location. The plot reveals that an electron samples a highly nonuniform coupling strength in completing one cyclotron gyration. Fig. 2b displays the electron velocity trajectories at the output plane. The solid circle is comprised of the initial values and dots are the values at the end of the run. The strongly perturbed orbits are the result of interaction with the cavity field. As a consequence of the second harmonic interaction, the phase bunching exhibits two heads. The corresponding electron spatial trajectories

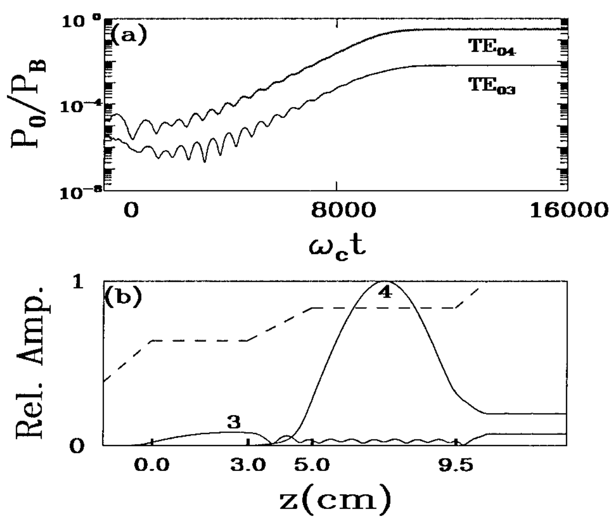


Fig. 1 Performance of a two coupled cavities oscillator. (a) Time evolution of output wave power. (b) Field profile at $\omega_c t = 1.6 \times 10^4$.

are shown in Fig. 2c which differs from Fig. 2b by $\pi/2$. As a result of the influence of non-uniform coupling strength, different bunching groups convert different amount of energy into radiation (Fig. 2b). However, if the coupling strength is not highly asymmetric with respect to the guiding center, averaging over a gyro period may smooth out the approximate result.

In order to compare with the results of two coupled cavities, the total length of three coupled cavities is kept at about L = 9.5 cm. The cavity and taper lengths are chosen to be $L_1=L_2=L_3= 2.5$ cm and $L_{12} = 1.5$ cm, $L_{23} = 1.6$cm. Figure 3a gives the time evolution of the $TE_{02}$, $TE_{03}$ and $TE_{04}$ modes which shows that they are coupled together and behave as a single global

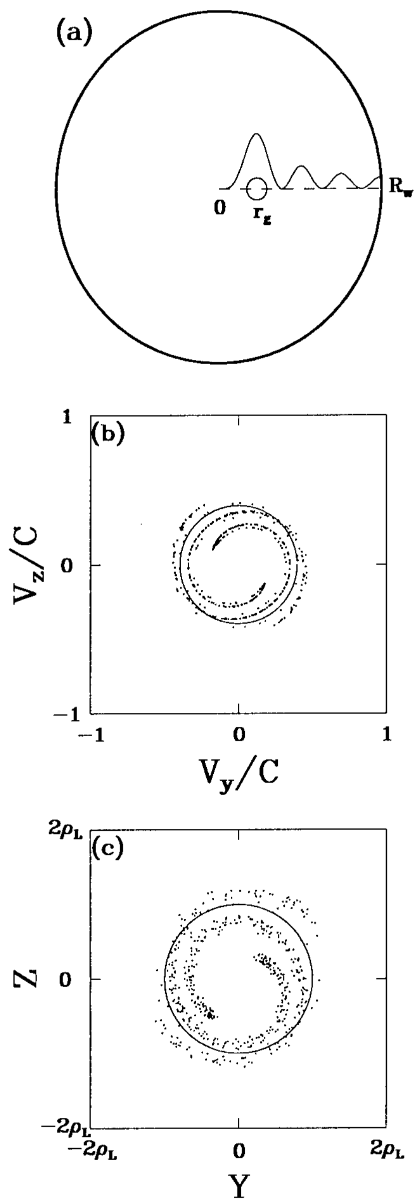


Fig. 2 Effects of radial inhomogeneity in electron-wave coupling strength on electron trajectories. (a) Radial profile of the electron wave coupling strength and beamlet location. (b) Electron $v_x$ versus $v_y$ at the output plane. (c) Corresponding electron x versus y, $\rho_L = 0.115$ cm.

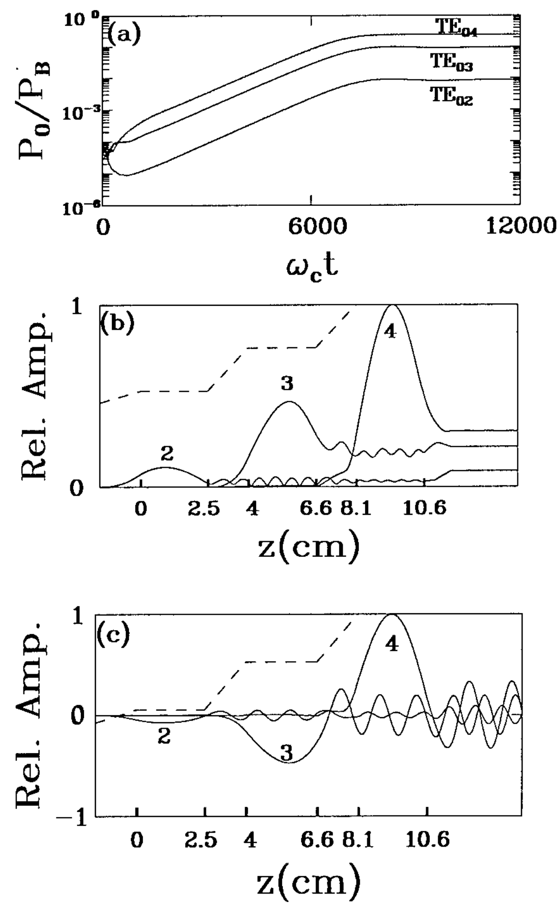


Fig. 3 Optimized performance of a three coupled cavities oscillator. (a) Time evolution of output wave power. (b) Averaged field amplitude profile at $\omega_c t = 1.2 \times 10^4$, (c) Instantaneous field profile at $\omega_c t = 1.2 \times 10^4$.

mode. Figure 3b displays the electric field amplitude profile (averaged over one wave period) at $\omega_c t = 2.4 \times 10^4$ which peaks at $L_p = 8.6$cm. In comparison with the result ($L_p$ = 7.3 cm) of two coupled cavities, the current result is much closer to the output plane. As a result, the cavity Q is reduced to 275. The dashed line in the figure is the profile of waveguide wall. Figure 3c shows the instantaneous electric field axial distribution for all three modes. The result indicates that the phase between cavity I and II differs by $2\pi$ but changes to $\pi$ from cavity II to III Although the Q is reduced by a factor of two, the efficiency ($\eta$=25%) is also decreased by almost a factor of two. Since the gyrotron is based on azimuthal phase bunching, the phase relationship among cavities can not be easily controlled by changing the electron transit time between cavities. . A typical electron completes about 20 cyclotron orbits in traveling through the three-cavity structure, but only 5 cyclotron orbits in passing through the individual cavity.

## IV. BANDWIDTH

The concept of extended interaction klystron was introduced in the early sixties in which the output is a short circuit slow wave structure. It was found that the synchronism between the beam electrons and the forwarded component of the standing wave in the output cavity plays an important role in determining the bandwidth and gain. The efficiency was improved due to the fact that the distributed modulation field gives rise to more efficient bunching, providing a larger fundamental RF beam current at the output gap. Enhancement in bandwidth as well as efficiency was observed in experiment. In a gyrotron oscillator, the bunching can be optimized by carefully profiling the waveguide wall. As a result, it is difficult to improve the efficiency of a single cavity oscillator by using multi coupled cavities oscillator. However, the bandwidth can be improved in principle by reducing the oscillator Q. This can be accomplished by

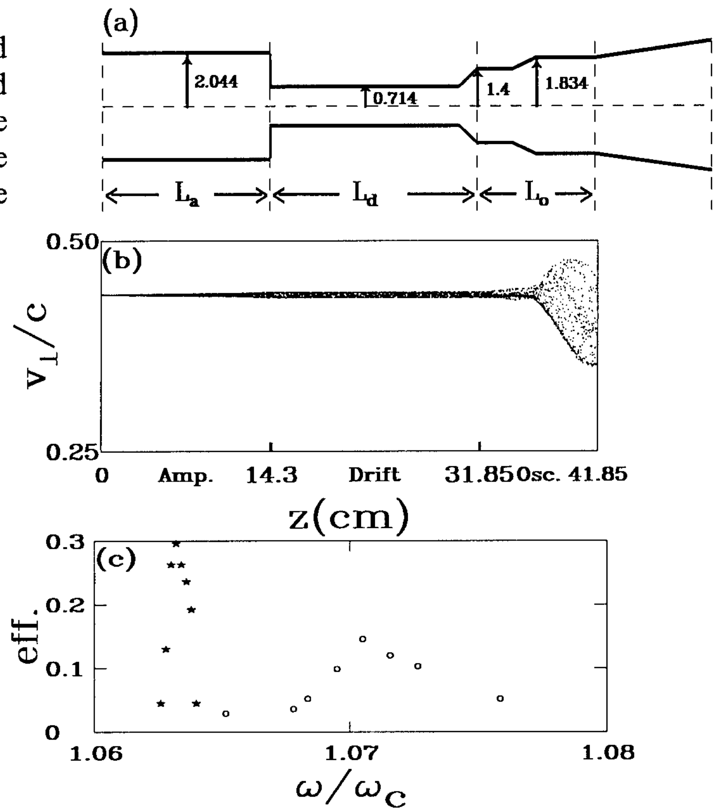


Fig. 4 Performance of inverted gyrotwystrons. (a) Configuration, amplifier section ($L_a$ = 14.3 cm, $R_a$ = 2.044 cm), drift section ($L_d$ = 17.55 cm, $R_d$ = 0.714 cm), and output section ($L_o$ = 10 cm). (b) Electron phase space ($v_\perp$ versus z) for using two coupled cavities as its output cavity. (c) Bandwidths of using two couple cavities (stars) and three couple cavities (solid dots) as its output cavity.

using a three coupled cavities because as has been shown (fig. 3), the peak of the wave field is shifted further to the output plane which tends to increase the output wave power $P_w$. In the case of an extended interaction gyrotron, a compromise between bandwidth and efficiency must be reached.

In order to address the issue of bandwidth enhancement by reducing the Q of the output cavity, the inverted twystron amplifier configuration (Fig. 4a) is used. The length of each section is chosen to be: $L_a$ = 14.3 cm (amplifier, $R_a$ =2.044 cm), $L_d$ = 17.55 cm (drift, $R_d$ = 0.714 cm), and $L_o$ = 10 cm (output). The frequency and power of input signal were varied to achieve the optimal output efficiency. The steady-state electron phase space ($v_\perp$ versus z) is shown in Fig. 4b. In the first two sections, electrons undergo pre-bunching and results in only perturbation of their trajectories with negligible energy loss. In the output section, electrons interact strongly with and converts their energies to the cavity field. Figure 4c compares the bandwidth of amplifiers using two and three coupled cavities as its output cavity. Simulation results show that the bandwidth of three coupled cavities (0.6%) is about three times the bandwidth of two coupled cavities (0.2%). The above simulations were carried out without the effect of resistive loading. To avoid the self-oscillation of input and output sections, the beam current was reduced to 10 Amps. As a result, the output efficiency of using three coupled cavities ($\eta$=15%) is lower than that of using 40A. By coating the output cavity wall with lossy material, the bandwidth and the beam current of a stable amplifier can both be increased. Currently, we are developing a numerical model which consists of input, bunching, and output sections. Drift sections are used to connect them. Each section can be a gyro-TWT, clustered cavity, or an extended interaction cavity. The newly developed code will be used to investigate the performance of multi-section modified gyroklystron amplifiers.

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**Collaborative Activities within MURI**

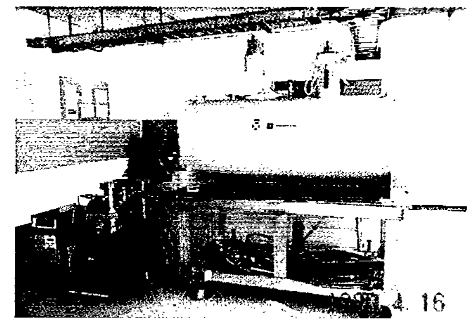
1. Provide magnetron injection gun(MIG) design for the proposed heavily-loaded 94GHz TE01 gyro-TWT experiments (with UC Davis).
2. Evaluate the performance of a new version of phigtron using MSEIC as its output cavity (with U. of Maryland).

# High Performance 94 GHz $TE_{01}$ Gyro-TWT Amplifier

## Objectives

- Extend DoD's TWT technology into millimeter range
- Develop stable W-band 100kW gyro-TWT amplifier

*50 kG Superconducting Magnet*



## Approach

- Gyro-TWT's offer wide bandwidth
- $TE_{01}$ mode transmits high power
- Mode-selective circuit and loss stabilize amplifier by suppressing competing modes

## Accomplishments

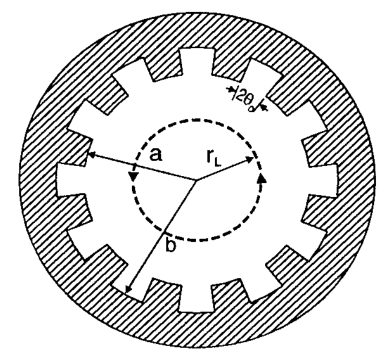
- 95 GHz, 100 kW gyro-TWT is under construction
  - MIG gun is being fabricated
  - Modulator tested for 100W CC-TWT
  - Mode-selective circuit developed
  - Stability codes determine needed loss
  - Large-signal code predicts $\eta = 20\%$

# 94GHz Sixth-Harmonic Gyrotron

## Objectives

- Reduce magnetic field needed by 94 GHz gyrotrons in order to make HPM systems lighter and more practical
- Develop 25-100 kW W-band high harmonic gyrotrons
- Basis for high-harmonic gyro-amplifiers

*12-Vane Slotted Circuit*




## Approach

- Operation at $s^{th}$-harmonic reduces magnetic field by factor of $s$
- Cusp gun produces needed axis-encircling electron beam
- Slotted circuit enhances interaction

## Accomplishments

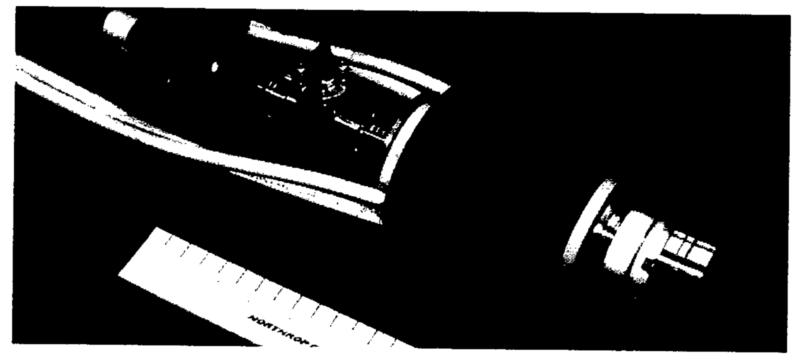
- Received two Northrop Cusp guns
- 94 GHz $6^{th}$-harmonic gyrotron design
  - 50 kW with 20% efficiency
  - Under construction
- 94 GHz $8^{th}$-harmonic gyrotron design
  - Employs permanent magnet

# Ka-Band Second-Harmonic Gyro-TWT Amplifier

## Objectives

- Improve stability and power level of gyrotron amplifiers
- Increase efficiency of our recent 200 kW second-harmonic gyro-TWT

*Northrop Grumman Cusp Gun*



## Approach

- Harmonic gyro-devices are more stable and yield higher power
- Sliced mode-selective circuit suppresses competing mode
- Axis-encircling electrons will yield full efficiency in linearly polarized mode-selective circuit

## Accomplishments

- 35 GHz, 60 kW gyro-TWT has been designed with $\eta$=24%

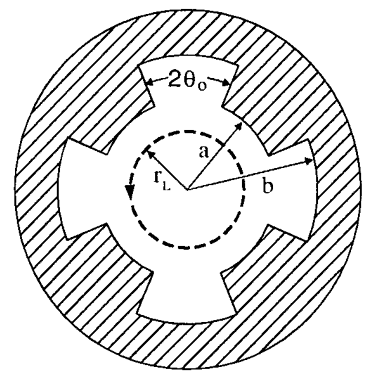
- Employs Northrop Cusp gun
- 0 dB coupler designed and tested
- Mode-selective circuit tested
- Stability codes determine needed loss
- Proof-of-principle yielded 200 kW

# High Efficiency Ka-Band Second-Harmonic Peniotron

## Objectives

- Improve device efficiency of Tohoku's recent third-harmonic $\eta$=35% peniotron
- Achieve device efficiency > 50% in harmonic gyro-device
- Foundation for peniotron-amplifiers

*4-Vane Slotted Circuit*




## Approach

- Axis-encircling electrons generate $m^{th}$-order azimuthal mode in $s^{th}$-harmonic peniotron if m=s+1
- Slotted circuit enhances interaction and allows stable, lowest-order mode to have desired $m^{th}$-order symmetry
- Cusp gun produces needed axis-encircling electron beam

## Accomplishments

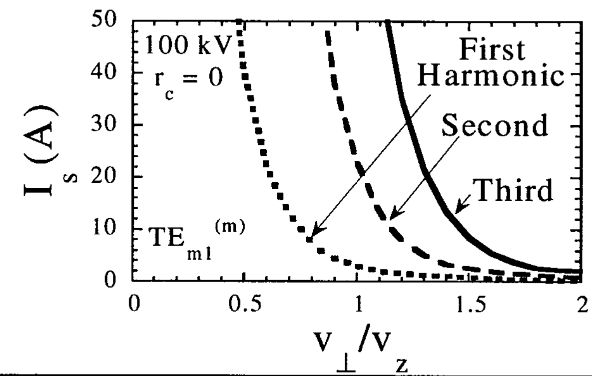
- Received two Northrop Cusp guns
- 35 GHz $2^{nd}$-harmonic peniotron design
  - 150 kW with 50% device efficiency
  - Employs Northrop Cusp gun

# High Power Second-Harmonic $TE_{02}$ Gyro-TWT Amplifier

## Objectives

- Develop stable W-band 500kW gyro-TWT amplifier

## *Start-Oscillation Current Increases with Harmonic Number*




## Approach

- Higher operating cyclotron harmonic allows higher stable beam current
- Low loss $TE_{02}$ mode handles high power
- Mode-selective circuit suppresses competing modes

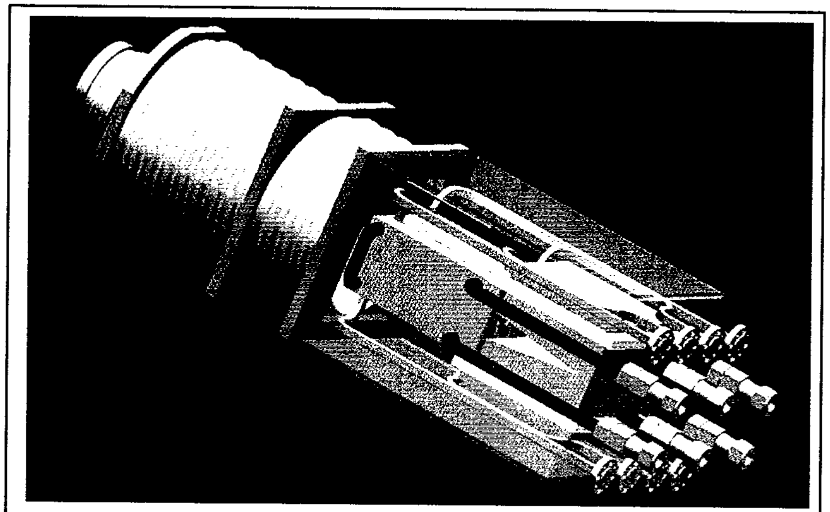
## Accomplishments

- 500kW W-band stable amplifier designed in collaboration with *Micramics*
- Two mode-selective circuits were developed

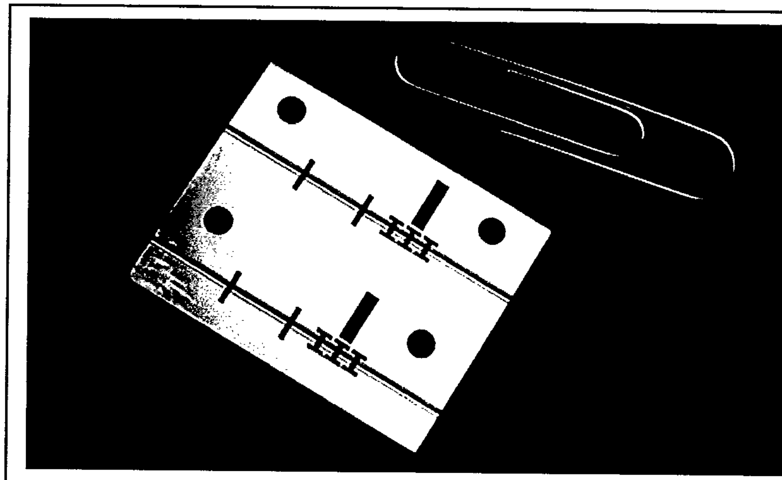
# UC Davis/Stanford Collaboration on High-Average-Power Modular W-band Klystrons

## Klystron Research Program

- Design high average power klystron at W-band
- Investigate alternative fabrication methods to provide efficient, modular, and cost effective RF source
- Improve modeling of three dimensional RF circuit
- Validate electron gun and beam transport performance
- Build and test a 100 kW peak, 1 kW average power tube



**Model of four klystrino module**



**LIGA klystrino circuit after EDM of beam tunnel**

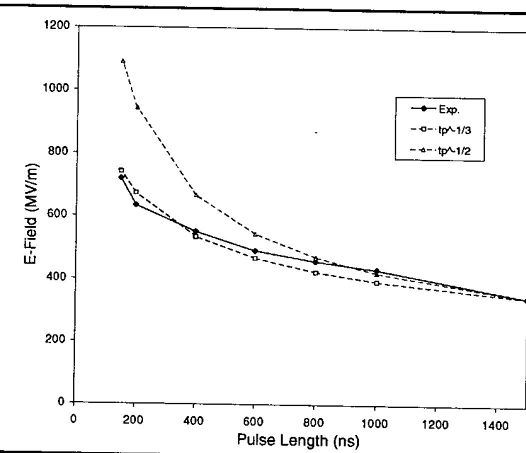
## Project Status

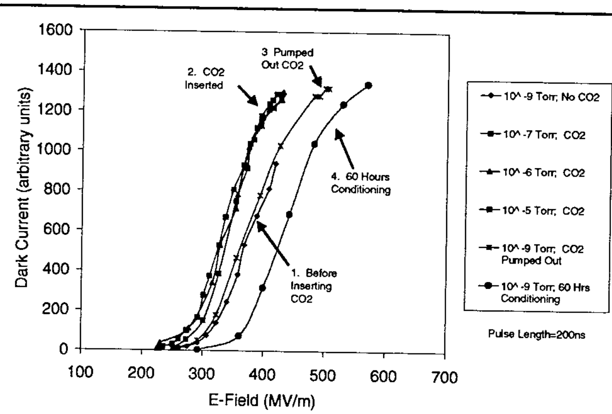
- LIGA fabrication of W-band cavities produced intrinsic Q's near theoretical values.
- Low voltage beam transport test successful, full voltage beamstick to be tested in April
- MAFIA and MAGIC used to produce accurate 2-D model of 3-D klystrino circuit
- LIGA fabrication of the final circuit layout in progress

# UC Davis/Stanford Collaboration on High Gradient RF Breakdown Studies

## RF Breakdown Program

- Investigate rf breakdown and understand the fundamental mechanisms involved in breakdown processes.
  - Explore pulse length and vacuum issues associated with rf breakdown.
- Investigate dark current, grain boundaries, oxidation, microparticle contamination.
- Test a variety of materials, and surface treatments.
- Increase RF breakdown threshold level.
- Reduce processing time of HPM devices.




## Project Status

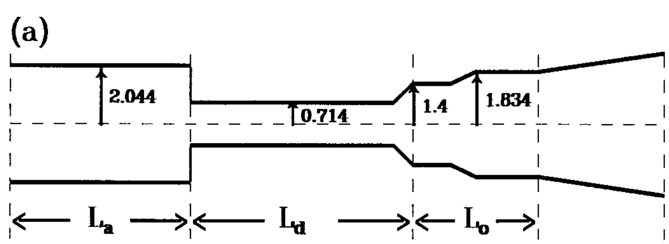
- When $CO_2$ was introduced into the cavity the dark current increased by a factor of two (left). The breakdown field remained comparable to measurements taken without $CO_2$. This indicates that dark current may not be directly related to breakdown.
- Both dark current and breakdown field remained approximately the same when Nitrogen was introduced into the system. Dark current appears to be gas specie dependent.
- Pulse length study: Between 800ns to 1500ns, the breakdown field followed a $\tau^{-1/2}$ time behavior. At shorter pulse lengths a transition from $\tau^{-1/2}$ to $\tau^{-1/3}$ occurs (top).

# UCLA/UMD Collaboration on Simulation on Modified Gyrotwystron Amplifier

## Goals

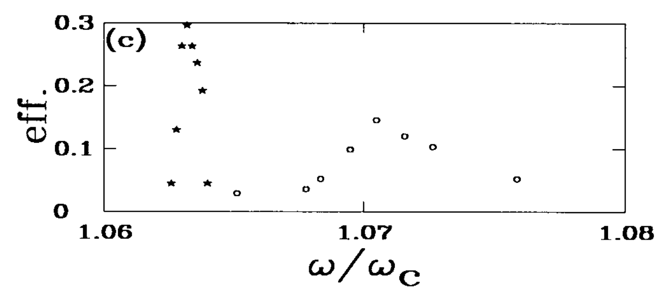
- Use mode selective extended interaction cavity ($TE_{02}/TE_{03}/TE_{04}$) as the inverted gyrotwystron output cavity to increase its bandwidth.
- Compromise between bandwidth and efficiency of the amplifier must be reached.

## Approaches




- Amplifier section $L_a$ =14.3 cm gyro-TWT
- Drift section $L_d$ = 17.55 cm
- Output section $L_o$ = 10 cm, extended interaction cavity

## Simulation Results




Parameters: $V_b$=70kV, I=10A, $\alpha$=1.5, $B_0$=6.617kG.

Output section uses

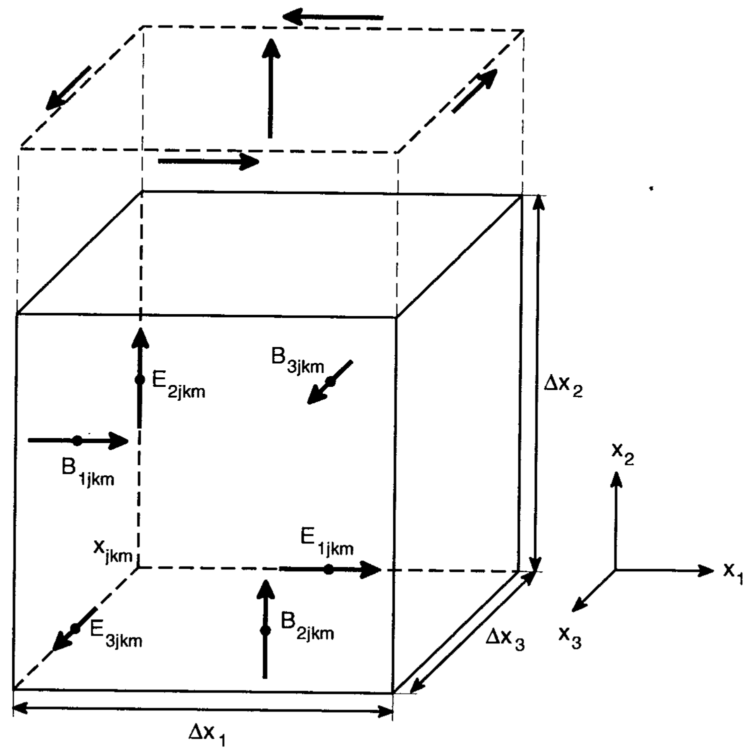
a. two coupled cavity eff : 25%
bandwidth : 0.2%

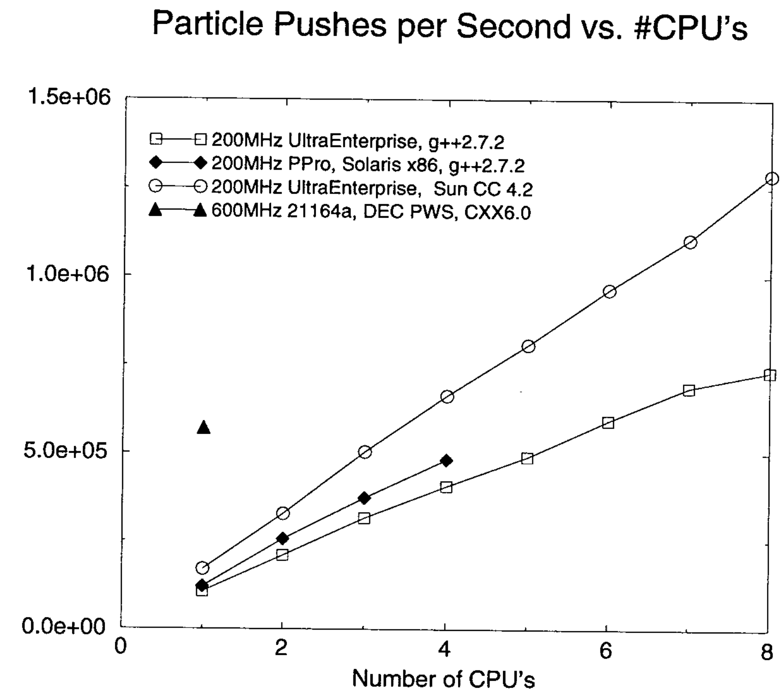
b. three coupled cavity eff : 15%
bandwidth : 0.6%

## Future Plans

- Develop Multi-section code
- Examine the effect of using the clustered cavity as the bunching cavity and high axial mode on the efficiency and bandwidth of the device.

# 3d/Parallel XOOPIC now functional



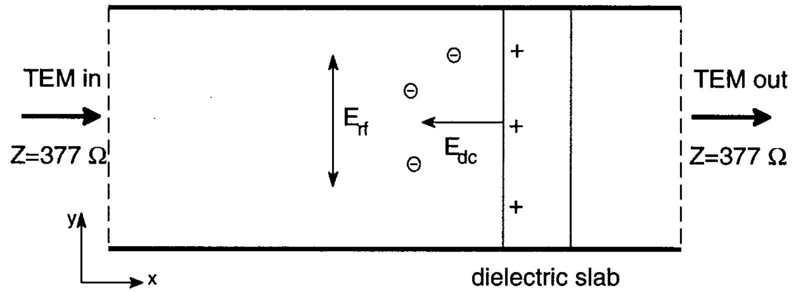




- Electromagnetic field components located as shown in Yee Diagram
- Exploded view shows integration of one field component)
- Particle integration via 3d extension of standard Boris Integrator
- Coupling via bilinear or charge conserving current weighting
- Significant work remains on boundary conditions and input file specification

- Cylindrical and Cartesian coordinates
- Relativistic and non-relativistic particles
- Automatic parallel decomposition in one or two directions
- Diagnostics currently independent by computational region
- Boundaries between computational regions are invisible to fields, particles see lower order magnetic field at edges
- Good scalability on balanced problems

## Single Surface Multipactor

Collaboration with Univ. Mich., Texas Tech.

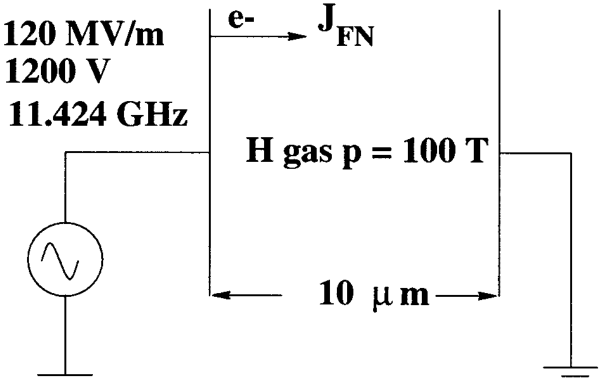



- Electrons gain energy in RF field
- Electrons charge surface, forming DC field
- Impact results in secondary emission and further charging
- Initial energy of secondaries directed away from surface
- DC field pulls electrons back toward surface
- Electron density can avalanche, resulting in deposition of large amounts of energy into surface
- Model uses energy and angular dependent secondary emission coefficient
- Emitted electron distribution includes reflected primaries, scattered primaries, and true secondaries.
- Observed high energy electron impact
- 1d and 2d models agree
- Upper impact energy energy cutoff discovered

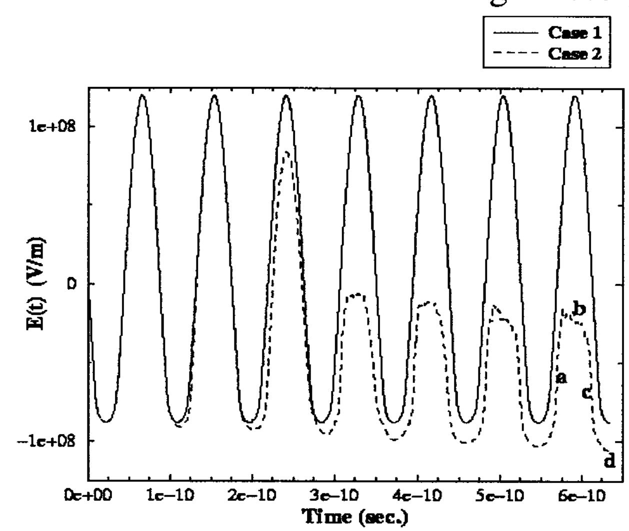
## Plasma Field Enhancement in an RF Gap

Collaboration with Stanford University, UC Davis

**E = 120 MV/m**
**V = 1200 V**
**f = 11.424 GHz**




- Studying the mechanism for 100x field enhancement observed in rf gap experiments
- Fowler-Nordheim emission with gas desorption




- Case 1: collisionless (no plasma) so no field enhancement
- Case 2: ions near the emitter enhance fields

# COMPLETE LIST OF PUBLICATIONS, PRESENTATIONS AT CONFERENCES, CO-AUTHORSHIPS, AND CONTRACTS AWARDED

## Book Chapters

V. L. Granatstein, G. Nusinovich, M. Blank, K. Felch, R. M. Gilgenbach, H. Guo, H. Jory, N. C. Luhmann, Jr., D. B. McDermott, J. Rodgers, and T. A. Spencer, "Gyrotron Oscillators and Amplifiers," to be published in "Advances in High Power Microwave Sources and Technologies," edited by R.J. Barker and E. Schamiloglu, IEEE Press, 2000.

"Breakdown in rf Structures" Advances in High Power Microwave Sources and Technologies, R. Barker, E. Schamiloglu, Editors, Ch. 10, A. Neuber, H. Krompholz, L. Laurent, Y. Lau, To be published, Nov. 2000.

"Dynamic Simulations of Mode Selective Extended Interaction Cavity for Widerband, High Power Gyrotron Applications," A. T. Lin, H. Guo, and V. Granatstein, accepted by IEEE Trans. On Plasma Science, special issue on HPM(1999).

Chapters of HPM book: Advances in High Power Microwave Sources and Technologies. Edited by R. J. Barker, and E. Schamiloglu
Chapter 7: Active Plasma Loading of High Power Microwave Devices, Y. Carmel, G. Nusinovich, A. Shkvarunets, C. Gralowski, F. Hegeler, A. T. Lin, O. Ishihara, D. Yound, and M. Armen

Chapter 11: Computational Techniques, J. W. Luginsland, T. Antosen, J. P. Verboncoeur, R. W. Lemke, L. Ludeking, P. M. Mardahl, A. T. Lin, Y. Y. Lau, and J. P. Blahovec.

Chapter 12: Alternate Approaches and Future Challenges, R. J. Barker, J. Benford, Y. Carmel, G. C. Caryotakis, J. Gaudet, R. Gilgenbach, V. Granatstein, G. Guest, M. Kristiansen, Y. Y. Lau, A. T. Lin, J. Nation, A. Neuber, and R. Umstattd.

J. P. Verboncoeur and K. L. Cartwright, "Plasma Pulse Shortening in a Relativistic Klystron Oscillator", Chapter 4: Pulse Shortening and Improved High Vacuum Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

P. J. Mardahl and J. P. Verboncoeur, "Parallel PIC Modeling", Chapter 11: Modeling and Computational Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

P. J. Mardahl, and J. P. Verboncoeur, "A Spectral Comparison of Two Methods of Enforcing Gauss's Law in Electromagnetic Particle-in-Cell Simulations", Chapter 11: Modeling and Computational Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

J. P. Verboncoeur, "Object Oriented Techniques", Chapter 11: Modeling and Computational Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

J. P. Verboncoeur, "Secondary Emission Model", Chapter 11: Modeling and Computational Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

J. P. Verboncoeur, "Monte Carlo Collision Model", Chapter 11: Modeling and Computational Techniques, in *Advances in High Power Microwave Sources and Technologies*, ed. R. J. Barker and E. Schamiloglu, IEEE Press.

### Journals

F. V. Hartemann, E. C. Landahl, A. L. Troha, J. R. Van Meter, H. A. Baldis, R. R. Freeman, N. C. Luhmann, Jr., L. Song, A. K. Kerman, and D. U. L. Yu, "The Chirped-Pulse Inverse Free-Electron Laser: A high-gradient vacuum laser accelerator", *Physics of Plasmas*. October 1999.

### Papers Accepted

K. L. Cartwright, J. P. Verboncoeur and C. K. Birdsall, "Loading and Injection of Maxwellian Distributions in Particle Simulations", accepted for publication in *J. Comput. Physics* (2000).

A. Valfells, J. P. Verboncoeur, and Y.Y Lau, "Space charge effects on multipactor on dielectric", accepted for publication in *IEEE Trans. Plasma Sci. 8th Special Issue on High Power Microwave Generation* (2000).

### Papers Submitted

D.B. McDermott, Y. Hirata, L.J. Dressman, D.A. Gallagher and N.C. Luhmann, Jr., "Efficient Ka-Band Second-Harmonic Slotted Peniotron," *submitted to IEEE Trans. on Plasma Science*, December, 1999.

Q. S. Wang, H. E. Huey, D. B. McDermott, Y. Hirata and N. C. Luhmann, Jr. , "Design of a W-Band Second-Harmonic Gyro-TWT Amplifier," *submitted to IEEE Trans. on Plasma Science*, December, 1999.

R.C. Stutzman, D.B. McDermott, Y. Hirata, D.A. Gallagher, T.A. Spencer and N.C. Luhmann, Jr., "W-Band Sixth-Harmonic Slotted Gyrotron," *submitted to the Int. Vacuum Electronics Conference*, 2000.

L.J. Dressman, D.B. McDermott, Y. Hirata, D.A. Gallagher, T.A. Spencer and N.C. Luhmann, Jr., "Highly Efficient Ka-Band Second-Harmonic Slotted Peniotron ," *submitted to the Int. Vacuum Electronics Conference*, 2000.

Y. Hirata, D.B. McDermott, A.T. Lin, T.H. Chang, K.R. Chu, and N.C. Luhmann, Jr., "Design of a Heavily-Loaded W-Band $TE_{01}$ Gyro-TWT," *submitted to the Int. Vacuum Electronics Conference*, 2000.

S.B. Harriet, D.B. McDermott, Y. Hirata, T.H. Chang, K.R. Chu, and N.C. Luhmann, Jr., "30 GHz Second-Harmonic Cusp-Gun Gyro-TWT Amplifier," *submitted to the Int. Vacuum Electronics Conference*, 2000.

L.R. Dressman, D.B. McDermott, Y. Hirata, D.A. Gallagher†, and N.C. Luhmann, Jr., "High Efficiency Ka-Band Second-Harmonic Peniotron ," *submitted to the IEEE Int. Conference on Plasma Science*, 2000.

R.C. Stutzman, D.B. McDermott, Y. Hirata, D.A. Gallagher, T.A. Spencer[2] and N.C. Luhmann, Jr., "94 GHz Sixth-Harmonic Slotted Gyrotron," submitted to the IEEE Int. Conference on Plasma Science, 2000.

Y. Hirata, D.B. McDermott, A.T. Lin, T.H. Chang, K.R. Chu, and N.C. Luhmann, Jr., "Heavily-Loaded W-Band $TE_{01}$ Gyro-TWT," *submitted to the IEEE Int. Conference on Plasma Science*, 2000.

S.B. Harriet, D.B. McDermott, Y. Hirata, T.H. Chang, K.R. Chu, and N.C. Luhmann, Jr., "Ka-Band Second-Harmonic Cusp-Gun Gyro-TWT," *submitted to the IEEE Int. Conference on Plasma Science*, 2000.

S.A. Rosenau, C. Liang, W-Y. Li, W-K. Zhang, C.W. Domier, N. C. Luhmann, Jr., "Frequency Multiplier Grid Arrays for Satellite Applications", submitted to: *25th International Conference on Infrared and Millimeter Waves,* Beijing, China, 12-15 September 2000.

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